All-Optical Signal Reshaping via Four-Wave Mixing in Optical Fibers

Ernesto Ciaramella and Stefano Trillo

Abstract—**A new scheme for all-optical signal reshaping is proposed and demonstrated. The strongly depleted mixing between a CW pump and a noisy nonreturn-to-zero (NRZ) signal in a common fiber can provide wavelength-converted signals exhibiting excellent intensity-noise cancellation. Numerical simulations confirm almost complete suppression of intensity fluctuations, simultaneously occurring at several different wavelengths.**

***Index Terms*—Optical communications, optical fibers, optical propagation in nonlinear media.**

I. Introduction

FUTURE all-optical networks will make use of in-line optical fiber amplifiers (OFA's) and optical cross connects (OXC's). Both of them, however, introduce optical noise, due to either amplified spontaneous emission (ASE) [1] or crosstalk [2]. If noise cumulates, it can finally result in significant intensity fluctuations in IM-DD channels (typically much larger on marks because of the signal–noise beating effect [1]). Hence, to prevent system impairments, signal regeneration should be implemented along the path. To this aim, it can be envisaged that all-optical techniques will be preferred to electrooptical schemes, because of transparency issues and higher operating bit rates.

Regeneration can be either 2R (re-amplification and reshaping) or 3R (with retiming). In both cases, a reshaping optical device would be crucial. This device should have a proper transfer function $P_{out} = P_{out}(P_{in})$, giving the dependence of optical output power P_{out} on input power P_{in}. In order to reduce intensity noise on the mark and space levels and to improve the signal extinction ratio, $P_{out}(P_{in})$ should be approximately constant for $P_{in} \approx \langle P_1\rangle$ and as close as possible to zero for $P_{in} \approx \langle P_0\rangle$ ($\langle P_0\rangle$ and $\langle P_1\rangle$ indicate the average power on spaces and marks, respectively). Furthermore, to be effective also for nonreturn-to-zero (NRZ) signals, reshaping should preserve the usual symmetry of NRZ-signal eye diagrams with respect to the middle line. Although the ideal reshaping function would be a step, noise cancellation was already demonstrated by using nonlinear interferometers, which exhibit sinusoidal transmission [3], [4]. Relying on interference, proper balance of those devices, which is rather difficult to obtain, is critical. Thus, additional components may be needed to improve reshaping [5].

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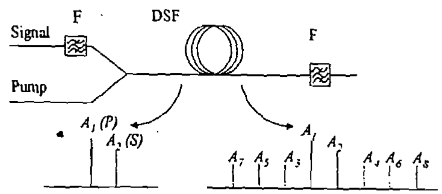

Fig. 1. Scheme for all-optical reshaping in DSF's. Signal and a CW pump produce high efficiency FWM signals, which, isolated by a tunable bandpass filter (F), can exhibit noise reduction.

In this letter we present a novel and simple reshaping technique, which does not require interference. In our scheme, all-optical reshaping comes from wavelength-conversion by means of high efficiency (i.e., strongly depleted) phase-insensitive four-wave mixing (FWM) [6]–[8], in dispersion shifted fibers (DSF's). This process gives various signals with fixed frequency separation, all modulated by the same binary coding as the input. Among these, reshaping can be obtained if the proper spectral component is optically selected.

II. Theory

The proposed scheme is illustrated in Fig. 1. A signal and a CW pump are injected into a 10-km-long DSF, with typical loss coefficient $\alpha = 0.025$ km^{-1} and nonlinear coefficient $\gamma = 2.2$ (W·km)$^{-1}$. The input signal is optically filtered, removing the less significant out-of-band noise, and polarization states of the signal and the pump are identical. Fig. 1 also illustrates the most relevant output components (pump and signal are labeled as A_1 and A_2, respectively), and the filter used to isolate one component.

As various parameters (such as D and pump power P_P) significantly affect the propagation in the DSF, operating criteria should be determined using the following nonlinear Schroedinger equation [6], [9]:

$$i\frac{\partial U}{\partial z} = -i\alpha U - \gamma|U|^2U + \frac{1}{2}\beta^{(2)}\frac{\partial^2 U}{\partial t^2} + \frac{i}{6}\beta^{(3)}\frac{\partial^3 U}{\partial t^3} \quad (1)$$

where U is the field envelope at the pump optical frequency [6], and constants $\beta^{(2)}$ and $\beta^{(3)}$ are related to the usual chromatic dispersion coefficient D and dispersion slope of the fiber [6]. To calculate the output power of each component and hence its transfer function, we can use a CW approximation of NRZ signal levels. This is well justified because the Kerr response time in fibers is much shorter than the time scale of the intensity fluctuations impairing system performance (electrical filtering

at the receiver removes high-frequency noise, with −3 dB-point at about 70% the bit rate). Hence input field is $U(z=0,t) = \Sigma_{j=1}^{2} A_j(z=0)e^{-i\omega_j t}$, where $A_j(z)$ is the complex amplitude of the jth wave (all A_j are CW, i.e., are not time-modulated) and ω_j is the detuning from the pump frequency ($\omega_1 = 0$, by definition).

At moderately low powers, higher-order generated sidebands can be neglected, thus the solution, given in terms of the two input waves A_1, A_2, and the generated idler A_3, describes the usual scheme for phase-insensitive wavelength conversion and phase-conjugation. As can be analytically derived, this scheme is not suitable for reshaping, even in the presence of pump depletion [7]. Indeed, the undepleted regime provides only a parametrically amplified replica of the input noisy signal. On the other hand, when power levels induce pump depletion, FWM-gain saturation reduces fluctuations on marks, but, due to a constant low-signal gain, noise on spaces is not reduced. Hence, output eye diagrams of both A_2 and A_3 components are not properly reshaped; moreover, when considering NRZ signals, they are affected by relevant asymmetries.

Nevertheless, we can envisage different behaviors for the higher order spectral components. For instance, if we consider A_4-wave, still the output power saturates for high P_{in}, but it also scales as $(P_{in})^2$ for low P_{in}, as can be derived from FWM theory [6]. Hence this component should also exhibit nonlinear attenuation on spaces. We check this qualitative argument by using a mode-truncation approach [8] that accounts for the evolution of the eight highest-power waves along the DSF. This large number of spectral components is needed because, under pump-depletion conditions, power transfer to the far FWM components (mainly A_5 and A_6) cannot be neglected. The approach is similar to that reported in [8], but is based on eight coupled ordinary differential equations (ODE's). Assuming $U(z,t) = \Sigma_{j=1}^{8} A_j(z)e^{-i\omega_j t}$, we derive from (1) the evolution ODE's for complex amplitudes A_j, which read as

$$i\frac{dA_j}{dz} = -i\alpha A_j - \beta_j A_j - \gamma\sum_{l,m,n=1}^{8} A_l^* A_m A_n \delta(\omega_m + \omega_n - \omega_l - \omega_i) \quad (2)$$

where β_j are the propagation constants ($\beta_j = (\beta^{(2)}/2)\omega_j^2 + (\beta^{(3)}/6)\omega_j^3$), and δ is the Kronecker delta. As (2) are not integrable analytically due to lack of conservation rules, they are integrated numerically over the $L = 10$-km DSF by means of usual ODE routines. Transfer function $P_{out} = P_{out}(P_{in})$ for the jth wave is obtained by considering $P_{out} = |A_j(L)|^2$, and $P_{in} = |A_2(0)|^2$.

Clearly, for given fiber parameters and P_P, transfer function is sensitive to j value, but also depends on the frequency detuning between signal and pump $\Delta\nu = \omega_2/2\pi$. As we will see, a reshaping behavior can be obtained at several FWM sideband orders. However, for the sake of simplicity, let us temporarily concentrate on the A_4-field, which could be the most interesting for applications as it exhibits typically the highest optical power. In Fig. 2, we report obtained P_{out} of this component as a function of P_{in} and $\Delta\nu$, when $P_P = 80$ mW and $D =$

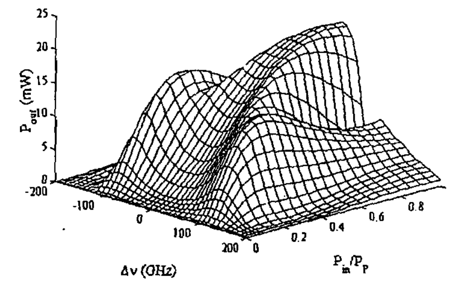

Fig. 2. Power of the A_4 wave as a function of both $\Delta\nu$ and normalized inp signal power P_{in}/P_P ($P_P = 80$ mW, $D = 0.35$ ps/nm/km).

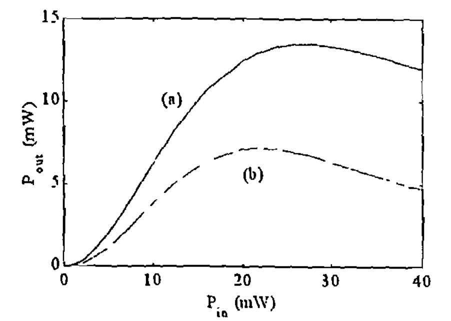

Fig. 3. Transfer function corresponding to the A_4 (a) and A_5 (b) spectr components for signal-pump frequency detuning $\Delta\nu = 100$ GHz ($P_P = 80$ m $D = 0.35$ ps/nm/km).

0.35 ps/nm/km at the pump wavelength. The slight asymmetı with respect to $\Delta\nu$ sign is due to the third-order DSF dispersio (0.07 ps/nm²/km). From this result, transfer function $P_{out}(P_{in}$ is obtained when $\Delta\nu$ is fixed: as shown, a wide frequency rang could provide all optical reshaping. As an example, curve (a) i Fig. 3 reports the function obtained for $\Delta\nu = 100$ GHz (≅ −0 nm at 1550 nm), which is a typical channel separation in WDI applications. Before the peak is reached, this function resen bles a sinusoid. As it is not exactly symmetric, compressio would be more effective on marks rather than on spaces. Th is an interesting feature, because in amplified links the intensit noise on marks is typically larger, so that it is typically the don inant source of Q-factor [hence bit-error-rate (BER)] degrad tion [1]. Furthermore, as the curve flattens after the maximun mark fluctuations that far exceed $\langle P_1\rangle$ are not bent toward tl space level, as it occurs in nonlinear interferometers [4].

This transfer function represents, to the best of our know edge, the first indication of reshaping capabilities of FWM single-pass fibers. Remarkably, although so far we have be mostly concerned with the A_4-wave, similar behavior is al obtained for other spectral components; indeed, curve (b) illu trates the transfer function for the A_5-wave (as defined in Fig. 1 which also indicates reshaping features. In the same configur tion, no matter what sideband with $j \geq 4$ we choose, simil features are obtained, although with different efficiency.

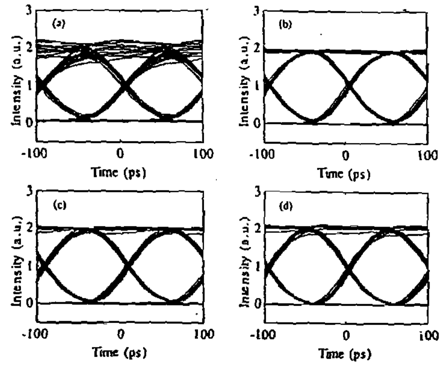

Fig. 4. All-optical reshaping at 10 Gb/s at different output wavelengths. Input eye diagram, which is affected by relevant ASE noise, is shown in (a). Reshaped eye diagrams are obtained by filtering either the A_4 (b), A_5 (c), or A_6 (d) component at the DSF output. In this case, $\Delta\upsilon = 100$ GHz, $D = 0.36$ ps/nm/km. $P_P = 80$ mW. Average input power is about 11 mW.

Above results are confirmed by system simulations, which numerically solve (1). The best operating condition (in terms of input signal peak power) agree with values determined using the above approach. A slight mismatch (typically less than 10%) can be observed, due to the truncation approximation used in (2). We also find that, due to nonlinear propagation, various FWM components can simultaneously be reshaped. To this aim, input power and D value are finely optimized, in order to match the peak positions of the various transfer functions. For instance, when D is slightly varied ($D = 0.36$ ps/nm/km), we get multiple-wavelength reshaping by setting 11-mW average input signal power. We consider a 128-bit input NRZ sequence at 10-Gbit/s affected by relevant ASE noise (25-dB optical signal-to-noise ratio), whose eye diagram is shown in Fig. 4(a). For a common receiver, i.e., with dc-coupled threshold [2], the intensity noise results in about 1-dB power penalty at BER = 10^{-9}. This signal propagates with a CW pump in a DSF ($P_P = 80$ mW, $\Delta\upsilon = 100$ GHz), then we optically select the output A_4-wave by using a filter with 0.4-nm bandwidth, centered at $\Delta\upsilon$ from the input signal. As shown in Fig. 4(b), this signal emerges well reshaped: fluctuations on both marks and spaces are almost cancelled, extinction ratio substantially improves, while the eye symmetry is preserved. Noteworthy, when selecting the A_5, and A_6 components, similar eye diagrams are also obtained [see Fig. 4(c) and (d)]. In all cases, full recovery of previous power penalty is predicted by means of a semi-analytical BER-estimation routine [9].

The latter example proves the feasibility of signal reshaping in a simplified situation. Indeed, the reshaper is placed just before a receiver, whose decision threshold is set in the middle between mark and space levels. Although this is usual in many practical systems [2], for particular applications the threshold is optimized to a different level to minimize noise impairments. In that case, reshaping gives *per se* limited benefits if performed only at the receiver, and, to further reduce impairments, should be performed in-line. To this aim, we note that the proposed technique is particularly suited whenever both reshaping and wavelength conversion are required (e.g., in some OXC's). For applications without conversion, it has the drawback that two similar devices should be cascaded to first convert and than restore the original wavelength. Hence the scheme becomes more demanding, even though this iteration further improves the overall reshaping function.

III. Conclusion

Wavelength conversion via FWM in optical fibers can provide all-optical reshaping. Operating conditions can be evaluated to obtain a transfer function reminiscent enough of an ideal step. Numerical simulations confirm this effect, showing excellent recovery of signal quality and simultaneous reshaping at multiple FWM components. The technique does not exploit interference, but rather uses a common single-pass DSF, hence is very stable, and could be cost-effective. Although this is demonstrated for a NRZ 10-Gb/s signal, the technique can be used also for RZ signals and, thanks to the extremely fast fiber nonlinearity, has no practical limitation on operating signal bit-rate (other techniques, relying on cross-phase modulation in semiconductor optical amplifiers, may be limited by the semiconductor recovery time).

References

[1] N. A. Olson, "Lightwave systems with optical amplifiers," *J. Lightwave Technol.*, vol. 7, pp. 1071–1082, 1989.
[2] E. L. Goldstein, L. Eskildsen, and A. F. Elrefaie, "Performance implications of component crosstalk in transparent lightwave networks," *IEEE Photon. Lett.*, pp. 657–659, 1994.
[3] I. D. Philips, A. Gloag, P. Kean, N. J. Doran, I. Bennion, and A. D. Ellis, "Simultaneous demultiplexing, data regeneration, and clock recovery with a single semiconductor optical amplifier-based nonlinear optical loop mirror," *Opt. Lett.*, vol. 22, pp. 1326–1328, 1997.
[4] B. Mikkelsen, S. L. Danielsen, C. Joergensen, R. J. S. Pedersen, H. N. Poulsen, and K. E. Stubkyaer, "All-optical noise reduction capability of interferometric wavelength converters," *Electron. Lett.*, vol. 32, pp. 566–567, 1996.
[5] B. Lavigne, D. Chiaroni, P. Gueber, L. Hamon, and A. Jourdan, "Improvement of regeneration capabilities in semiconductor optical amplifier-based 3R regenerator," in *Proc. Optical Communication Conf. (OFC'99)*, San Diego, CA, Paper TuJ3.
[6] G. P. Agrawal, *Nonlinear Fiber Optics*. New York: Academic, 1995.
[7] G. Cappellini and S. Trillo, "Third order three wave mixing in single mode fibers: Exact solutions and spatial instability effects," *J. Opt. Soc. Amer. B*, vol. 8, pp. 824–840, 1991.
[8] S. Trillo and S. Wabnitz, "Dynamics of the nonlinear modulation instability in optical fibers," *Opt. Lett.*, vol. 16, pp. 986–988, 1991.
[9] M. Jeruchim, "Techniques for estimating the Bit Error Rate in the simulation of digital communication systems," *IEEE J. Select. Areas Commun.*, vol. 2, pp. 153–170, 1984.